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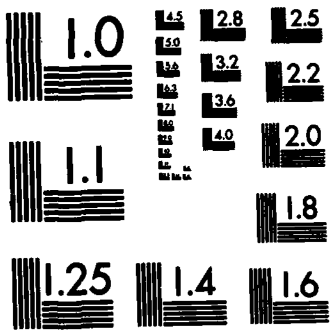

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

One of the most fundamental challenges of working in the ocean environment is the establishment of a geodetic control system, similar to the more familiar geodetic networks on the earth's land areas. Applications of ocean bottom control network are numerous, which are well identified by the marine community.

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The present paper discusses the concept details and developes the mathematical model for the system. Some simulated results of this novel approach are also included.

USE OF GPS

IN

OCEAN BOTTOM CONTROL

by

Muneendra Kumar
Hydrographic/Topographic Center
Defense Mapping Agency
Washington, D.C. 20315
and
Narendra K. Saxena
Department of Civil Engineering
University of Hawaii
Honolulu, Hawaii 96822

ABSTRACT

One of the most fundamental challenges of working in the ocean environment is the establishment of a geodetic control system, similar to the more familiar geodetic networks on the earth's land areas. Applications of ocean bottom control network are numerous, which are well identified by the marine community.

The NAVSTAR constellation of the Global Positioning System (GPS) provides a unique capability. The expected visibility of its four to seven satellites anywhere anytime on the earth's surface will enable instantaneous in real time positioning of a buoy, thus eliminating complex mathematical modeling of its motion. This buoy can simultaneously be triggered to measure ranges to a network of ocean bottom transponders through acoustic link, thus replacing the conventional expensive use of a ship. The concept takes advantage of a double pyramid, which is formed between GPS satellites and the transponders linked via buoy. The measured ranges, solved in the geometric mode through the least squares method, will thus provide geodetic positions of transponders.

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INTRODUCTION

The ocean environment presents a set of conditions under which we still are not accustomed to operate. One of the most fundamental challenges is the establishment of a geodetic control system, similar to the more familiar geodetic networks on the earth's land areas. Thus, the effort to obtain accurate marine geodetic measurements in the ocean and the techniques (or design of experiments) to utilize these measurements need an innovative approach.

The requirements for solving various interdisciplinary problems using precise and accurate marine geodetic surveys are available in Saxena (1975). Similarly, applications of an ocean-bottom control network are numerous and well identified in the marine community (Saxena, 1980).

In this direction, the NAVSTAR constellation of the Global Positioning System (GPS) provides an unique capability. Besides all other currently available techniques for navigation or geodetic applications in the ocean areas, the GPS would be the most versatile in its utility and global availability, when fully operational. The expected visibility of its four to seven satellites anywhere anytime on the earth's surface will enable instantaneous in real time positioning of a buoy geometrically. The knowledge of such real time positions will thus eliminate complex mathematical modeling of buoy motion on the ocean surface.

At any instant, when the buoy position is being obtained from the GPS, the buoy can simultaneously be triggered to measure ranges to a network of ocean bottom transponders through acoustic links. The concept takes advantage of a double pyramid (Figure 1), which is thus formed between the GPS satellites and the transponders linked via the floating buoy. The use of buoys is extremely advantageous as it gives more flexibility and will replace the conventional ships and their expensive budgets.

The measured ranges for any instantaneous double pyramid will constitute a geodetic "event" and these events are solved using the geometric mode (Mueller et al., 1973; Kumar, 1976) through the least squares method providing a geodetic control transponder network in the marine areas. The present paper discusses the concept details, developes the mathematical model for the system and analyzes some simulated results of this novel approach.

2. GEOMETRIC POSITIONING

Figure 1 constitutes a double pyramid, one "inverted" above the ocean between the GPS constellation and the buoy and the other "normal" underneath between the buoy and the transponders. The following subsections include some pertinent details about the GPS ranging and the acoustic links involved in the system.

2.1 The Inverted Pyramid

Range measurements to the GPS are performed electronically by code correlation on each of two coherent L-band frequencies for first-order atmospheric refraction correction. The geometric range between the receiver and the satellite transmitter plus the effect of clock synchronization error between them is known as pseudo range. Other error sources are given in Fell (1980).

It is assumed here that the geodetic receivers are capable of ranging to multiple GPS satellites simultaneously and two or more independent receivers located at different buoys or ground stations can generate simultaneous range observations (Ward, 1982). The main function of an inverted pyramid observation or "event" is to provide real time instantaneous buoy position in the GPS coordinate system (Figure 2a).

The uncertainty of a GPS range observation is currently estimated in the range 0.5 to 1.0m (Ward, 1982) and positional recovery in a navigational mode (or the inverted pyramid in this paper) are conservatively anticipated at this time as 10m in each coordinate axis.

2.2 The Normal Pyramid

Position determination of marine control points including performance analysis of acoustic navigation systems and net-unit configurations is under extensive study with the marine technologists (Knowles and Roy, 1972; Saxena, 1975; Durham et al., 1975; Yamazaki, 1975; Smith et al., 1975; Spindel et al., 1975; Saxena, 1976 and 1981). The typical high resolution acoustic navigation technique considered here is a pulse positioning system (PPS). The PPS employs a transducer emitting acoustic pulses at a controlled repetition rate and acquiring "replied" data from a set of bottom-moored acoustic transponders (Spindel et al., 1975). The slant range between the buoy and the transponders is estimated from the measured acoustic round trip travel time.

The rms error in the estimation of range with an optimum pulse system is approximately given as (Spindel et al., 1975):

$$\sigma_R = \frac{2Tc}{\sqrt{S}} \qquad (1)$$

where c is the sound velocity, T duration time for a rectangular pulse, S the peak signal to noise ratio at the output of the matched filter and R the slant range measured (Figure 2b). This paper also estimates σ_R to be about 1.5m for ranges between 5 to 15 km.

3. MATHEMATICAL MODEL

The detailed discussion on the geometric mode solution of a topocentric range is available in (Krakiwsky and Pope, 1967; Mueller et al., 1973; and Mueller et al., 1975). Figure 3 shows the geometry for range r_{ij} between any transmitter $P_i(u_i, v_i, w_i;\ i = 1, 2, 3, \ldots)$ to a receiver $Q_j(u_j, v_j, w_j;\ j = 1, 2, 3, \ldots)$, say between the GPS satellite and the buoy in the inverted pyramid configuration. (Note: At the same instant, the range R_{jm} between the buoy and the moored transponder in the normal pyramid is implied.) Then, the following relations in the earth-fixed coordinate system can be written:

$$F_{ij} \equiv \left[(u_j - u_i)^2 + (v_j - v_i)^2 + (w_j - w_i)^2\right]^{1/2} - r_{ij} = 0 \qquad (2)$$

$$\text{and } F'_{jm} \equiv \left[(u_j - u_m)^2 + (v_j - v_m)^2 + (w_j - w_m)^2\right]^{1/2} - R_{jm} = 0 \qquad (3)$$

where the u-axis is oriented towards the Greenwich Mean Astronomical Meridian and the w-axis towards the Conventional International Origin (both as defined by the Bureau International de L'Heure). Here the v-axis forms a right-handed system with u and w, and with u defines the average geodetic equator. For actual observations, equations (2) and (3) would require certain modifications to represent systematic and random error sources (Fell. 1980; Hui. 1982; Wells et al., 1982; Harman, 1982).

These basic mathematical models are solved through trigonometric computations based on an event (Reilly et al., 1972), in inverted and/or normal pyramid mode. The geometry of solution is stronger for an event which includes more than four satellites or transponder stations (Blaha, 1971a; Escobal et al., 1973; Smith et al., 1975; Saxena, 1976) and the optimal survey pattern for the normal pyramid will change with the water depth relative to station chords (Smith et al., 1975). As the system extends with the increase of "i", "j", and/or "m", the model (equations (2) and (3)) becomes overdetermined and the unknown transponder position parameters are then recovered through a least squares adjustment.

3.1 Observation Equation

The equations (2) and (3) are linearized by a Taylor series expansion about the preliminary values of the satellite and buoy positions, transponder stations' coordinates and the observed ranges r_{ij} and R_{jm} to obtain observation equations (Uotila, 1976) in the following form:

$$BV + AX + W = 0 \tag{4}$$

In the present paper, as a first step, a simpler adjustment procedure is adopted. The equation (2) is not linearized and the inverted pyramid is solved only to obtain the initial approximate buoy positions (u_j^o, v_j^o, w_j^o) for use in any normal event at time t_k (Figure 1). For range observation R_{jm} (equation (3)), equation (4) is then defined as:

$$B_{jm} = \frac{\partial F'_{jm}}{\partial R_{jm}} = \left[\begin{array}{c|c|c} 0 & -1 & 0 \end{array}\right]$$

$$A_{jm} = \frac{\partial F'_{jm}}{\partial u_m^o, \partial u_j^o} = \left[\begin{array}{c|c} a_{jm} & -a_{jm} \end{array}\right]$$

$$a_{jm} = \left[\frac{u_m^o - u_j^o}{R_{jm}} \quad \frac{v_m^o - v_j^o}{R_{jm}} \quad \frac{w_m^o - w_j^o}{R_{jm}}\right]^T$$

$$X_{jm} = \left[\begin{array}{ccc|ccc} du_m & dv_m & dw_m & du_j & dv_j & dw_j \end{array}\right]^T$$

$$W_{jm} = R_{jm}^c \text{ (computed)} - R_{jm}^o \text{ (observed)}.$$

The R_{jm}^c value is computed from the approximate buoy and transponder positions to evaluate misclosure vector W_{jm}. Also, the design matrix B_{jm} here becomes a negative unit matrix $[-I]$ and the residual matrix V_{jm} then corresponds directly to the observed ranges R_{jm}.

3.2 Normal Equation

If P is the weight matrix for the observed ranges, then the variation function Φ to be minimized is given as:

$$\Phi = V^T P V + X^T P_x X - 2K^T (AX - V + W) \tag{5}$$

where

$$P_x = \left[\begin{array}{c|c} P_{x_j} & \\ \hline & P_{x_m} \end{array}\right]$$

K ≡ Vector of Lagrange multipliers.

After enforcing the minimum condition in equation (5) and eliminating K and V, the normal equations for buoy and transponder positions can be written as:

$$\begin{bmatrix} N_{jj} & N_{jm} \\ N_{mj} & N_{mm} \end{bmatrix} \begin{bmatrix} X_j \\ X_m \end{bmatrix} + \begin{bmatrix} U_j \\ U_m \end{bmatrix} = 0 \tag{6}$$

In this development, the buoy positions (X_j) are only necessary to provide the link between the GPS constellation and the transponders and to develop the normal equations (6). As the "nuisance" parameters X_j are eliminated, the final form of the normal equations is then obtained in the following form:

$$NX_m + U = 0 \tag{7}$$

4. ANALYSIS OF GEOMETRIC POSITIONING

In the current analysis, a typical rectangular network of 25 transponder stations is visualized with a grid spacing of 10 km in near shore areas (Figure 4). The simultaneous "events" to a buoy position were considered for two cases, where four and six transponder stations participated in an event through acoustic ranges. This scenario can be extended to include 3 or more stations from an adjoining coastline.

In the normal equations the scale definition is provided implicitly from the observed ranges, while theoretically speaking, definitions for origin and orientation are required from external information. One choice for these external conditions is the "inner" constraints or free adjustment (Blaha, 1971b), which then produces a solution with covariance matrix having minimum trace. This implies that the center of gravity of all transponder stations, as computed using initial coordinate values, will not change after the adjustment and the sum of rotations of points around all three coordinate axes will be zero.

Further interpretations are based here on a similar extensive study (Kumar, 1976) carried out by the first author on geometric mode positioning. The preliminary results have been extrapolated for the "normal" transponders pyramid (using a 15m recovery estimate in respect to instantaneous buoy position from GPS in the inverted pyramid mode) from solutions 1-13 and 1-14 of the study (Kumar, 1976) through further error analysis and Table 1 gives a brief summary of the four and six station configurations.

Table 1

Relative Position Recovery for a Transponder Network

No. of Transponders Co-observing in an event	σ_R (Acoustic Range in the normal pyramid)	Estimated Standard Error in Buoy Position from the Inverted Pyramid	Relative Position Recovery (Extrapolated)[1]	Remarks
4	1.5m	15m	1.5 to 2m	Recovery susceptible to critical configuration
6	1.5m	15m	0.8 to 1m	

[1]Kumar, 1976.

A more detailed error analysis is in hand and the results of the extended study will follow. However, preliminary investigations done so far show great promise.

5. SUMMARY

The double pyramid approach gives more flexibility in using the GPS for marine control by replacing conventional (and costly) ships and eliminating mathematical modeling of ship's velocity. The paper presents the concept demonstrating the potential of geometric positioning of a transponder network. Further investigations (Kumar and Fell, 1983) in respect to systematic and random errors, optimal configuration in selecting the satellites and transponders in the double pyramid, and variations in network geometry and definition are under way. Using GPS, the double pyramid geometric positioning offers a novel approach for ocean bottom geodetic control networks with many applications.

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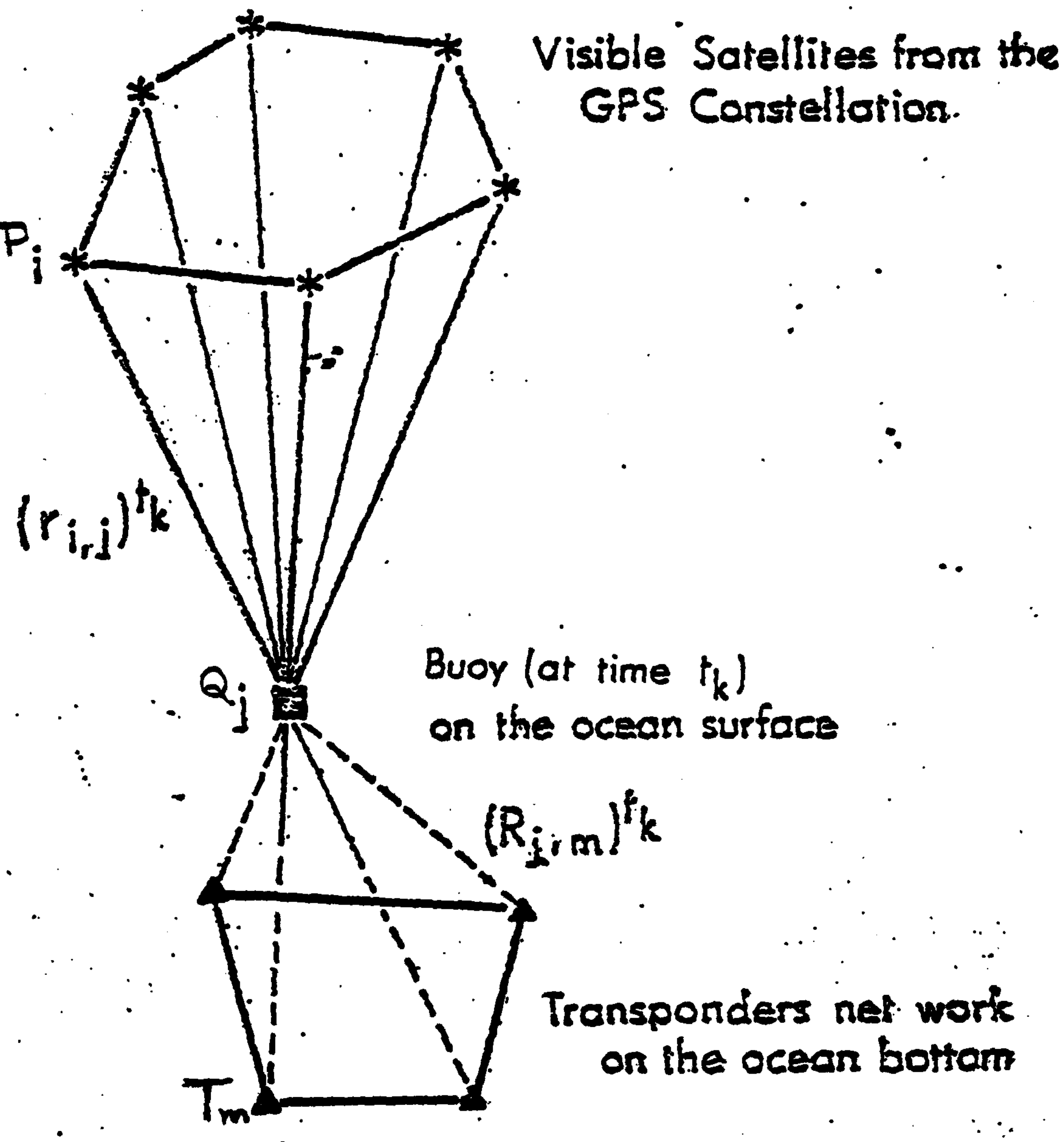

Figure 1: Double Pyramid Configuration for Observation of a Complete Event

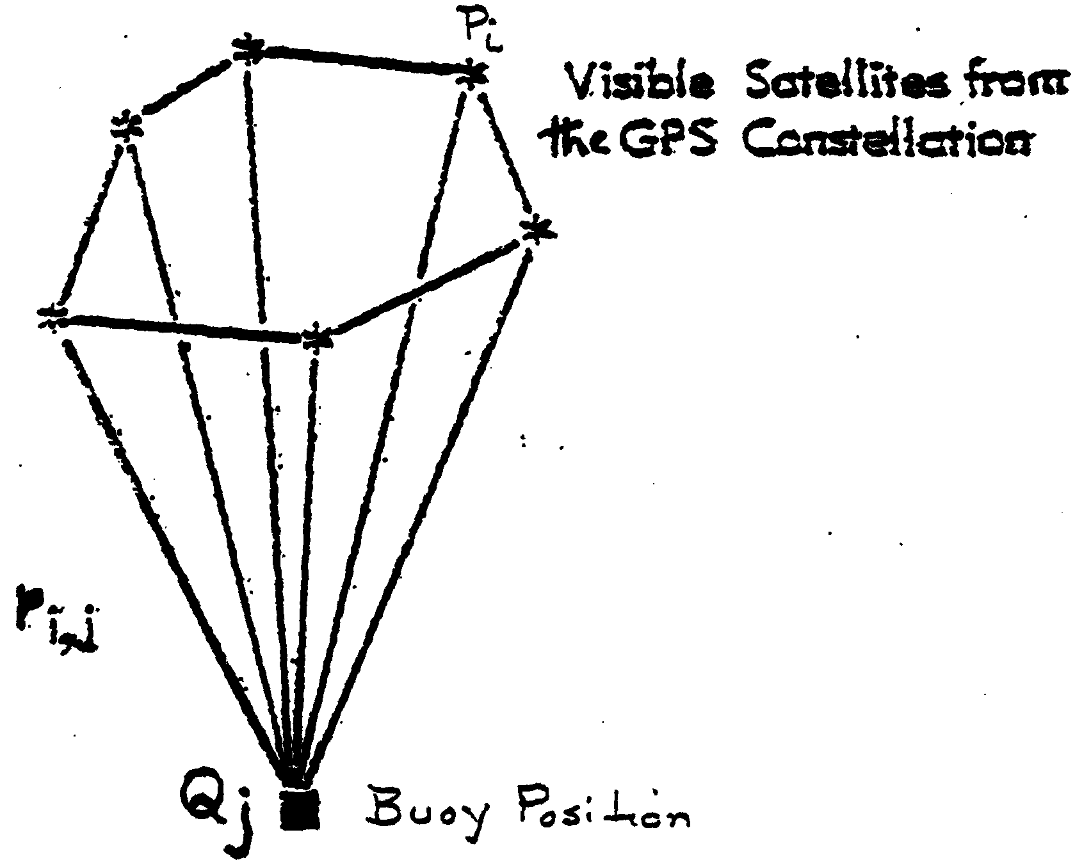

Figure 2a: An Event with Observations to Multiple Satellites.

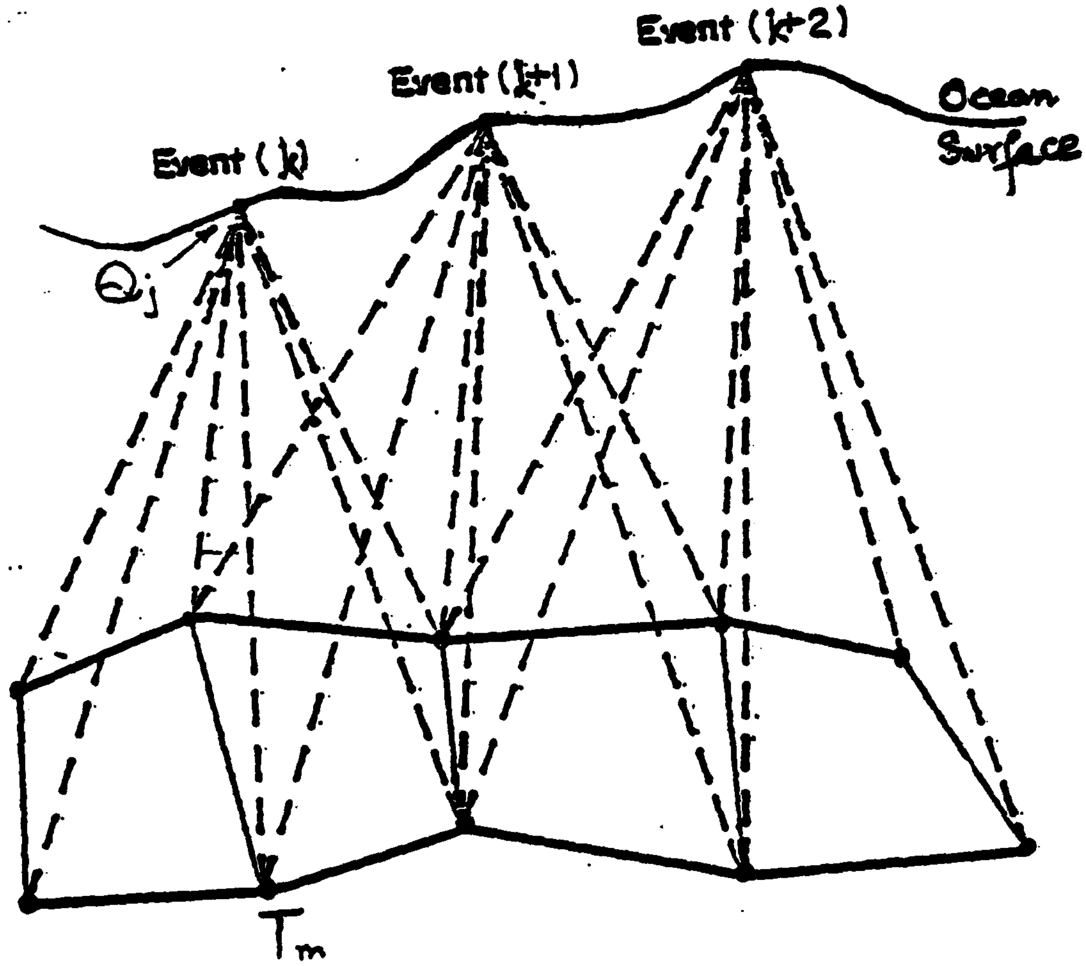

Figure 2b: An Event with Observations to Multiple Transponders (T_m) from Buoy Positions (Q_j).

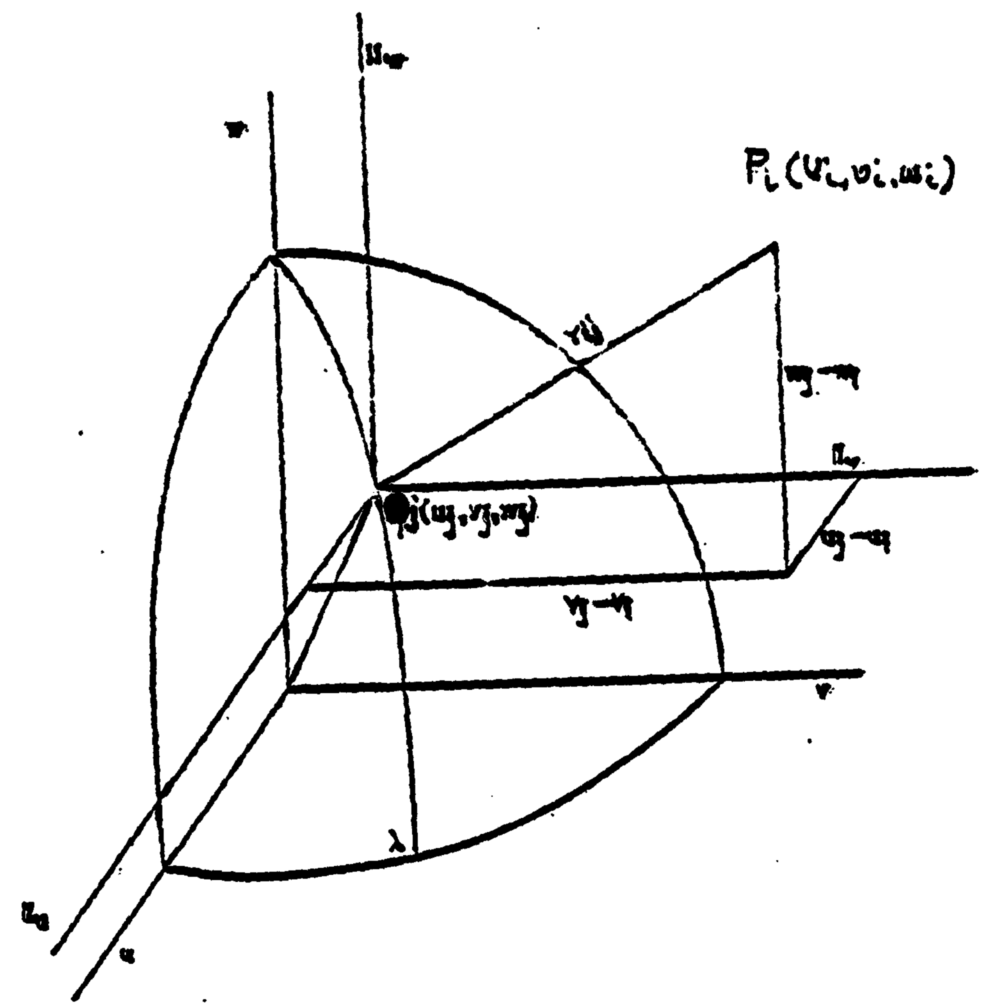

Figure 3 : Geometry for a Topocentric Range

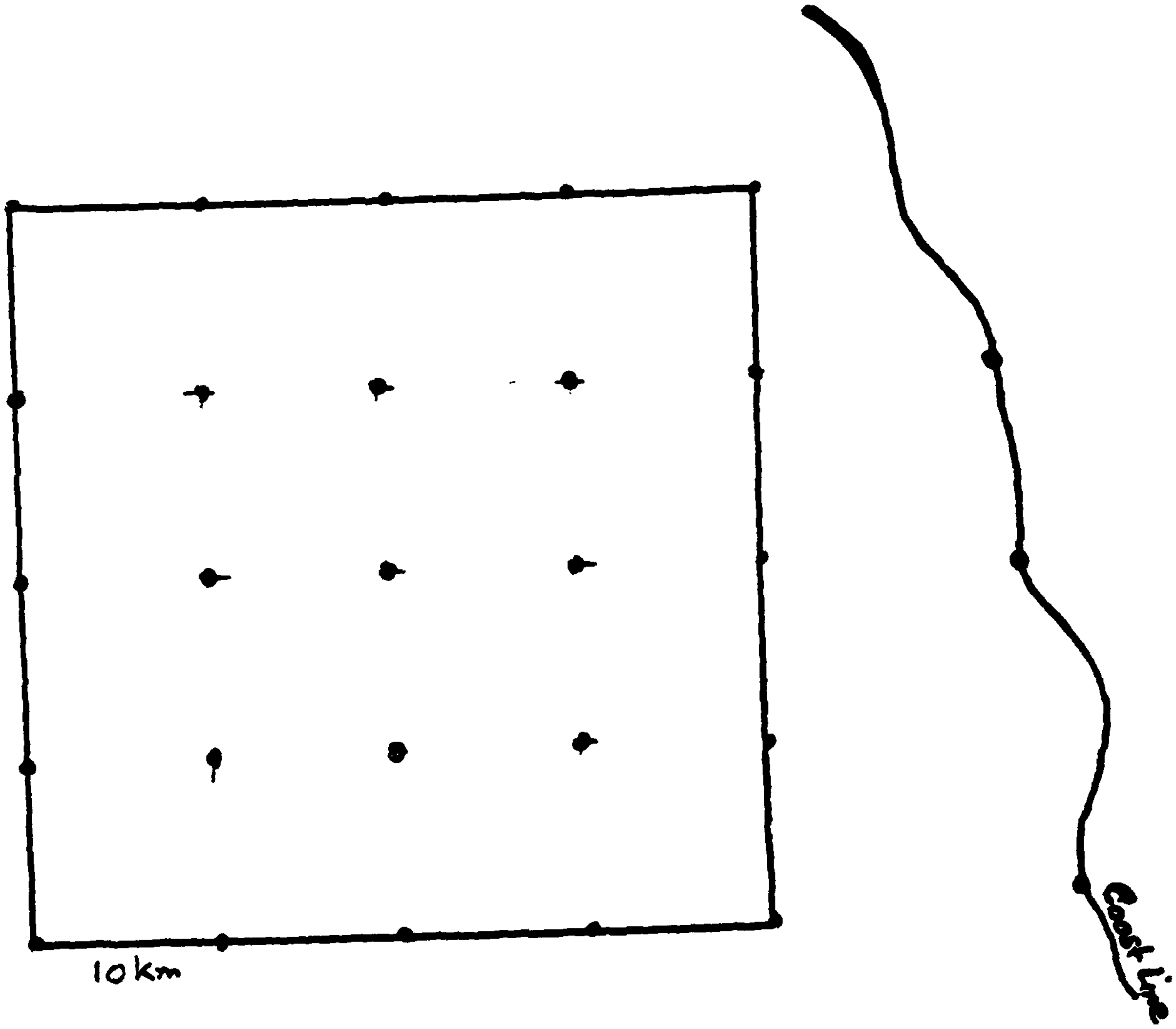

Figure 4: A Typical Transponder Stations Network for Near Shore Areas.

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